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Title: Experimental Investigation of Turbulent Prandtl Number and Reynolds Analogy in Transitional and Post-Transitional Boundary Layers

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## SYNOPSIS

This program has been proceeding smoothly and is following the projected schedule. The major progress during the past year has been in these areas:

(A) Calibration and modification of the heated test wall,

(B) Development of data acquisition and reduction programs for fluid mechanics and heat transfer measurements,

(C) Measurements of the baseline experiment on a flat surface, and

(D) Literature search, design and fabrication of a three-wire probe for measuring Reynolds heat flux in a transitional boundary layer.

The preliminary results of mean flow and temperature from the baseline experiment indicated that the test facility and apparatus are well controlled and adequate for conducting studies of natural transition boundary layers. The distribution of skin-friction coefficient and Stanton number has indicated a breakdown of Reynolds analogy in the transitional flow and was not recovered even in the fully turbulent flow regime in the present wind tunnel test section.

## ACHIEVEMENTS OF THE FIRST YEAR

The progress in each area is reported below:

(A) Calibration and Modification of the Heated Test Wall

The heated test surface was designed in a composite manner as shown in Fig.1. The thermocouple junctions were embedded in the grooves cut through a rubber spacer which serves as the buffer material for protecting the thermocouple junctions. One hundred eighty-four thermocouples were strategically deployed as shown in Fig.2 in order to capture the three-dimensionality of the transitional flow. Since the surface was very large (8 ft x 3 ft) compared with the thickness of the wall (0.25 in), it was difficult to keep the test wall flat in a vertical position. The waviness of the wall had caused earlier boundary layer transition from laminar to turbulent flow. This problem was not solved untill March 1990 when a special vacuum system was applied to the back of the test wall.

It has been a tedious task to calibrate the 184 embedded thermocouples in a range from 15 C to 50 C. Since the wind tunnel is an open type (Fig.3), the whole room is used as a control chamber to obtain a calibration for each individual thermocouple.

(B) Development of Data Acquisition and Reduction Programs

The data acquisition and reduction consist of two major areas: fluid mechanics and heat transfer.

(a) Fluid Mechanics

A MetraByte DAS-20 A/D 16-channel data acquisition board, capable of measuring data up to 100kHz, was installed in a 80386 microprocessor based personal computer. A sample-and-hold board was used for taking data simultaneously from up to four channels. The following data acquisition and reduction programs have been developed:

Program 1 for single hot wire: taking 20 kHz for 2 seconds and 2kHz for 20 seconds for each physical location. Mean velocity profiles, boundary layer integral parameters, and streamwise Reynolds normal stress were reduced.

Program 2 for two cross wires: one for $\overline{u'v'}$, another for $\overline{u'w'}$. Reynolds shear stresses were reduced.

Programs 3&4 for reducing skin friction coefficients: one for laminar flow, another one for turbulent flow.

Program 5 for checking momentum balance and two-dimensionality: This program is used also for estimating skin-friction coefficients in the transitional boundary layer.

(b) Heat Transfer

A Fluke switch controller, capable of scanning 1,000 channels, was equipped with one hundred channels of low-voltage, radiation shield thermocouple modules. A Fluke precision multimeter with 0.1 uv resolution was used as a low voltage A/D converter for collecting wall temperature data. Three programs have been developed for measuring wall temperature as well as the temperature distribution in the boundary layer.

Program 6 for wall temperature measurement: a total of 190 thermocouples were scanned three times for each triggering of measurement. The scanning rate was set at 1 Hz. The measurements included 180 wall thermocouples, two ice bath reference junctions, three reference junctions in the isothermal box, one in the freestream, one in ambience, and three at the back of the test wall. The surface heat transfer coefficient (Stanton number) can be obtained using this program.

Program 7 for temperature profile in the boundary layer: a 3 mil, spot welded boundary layer temperature probe was designed and fabricated. Mean temperature profile and enthalpy thickness can be reduced using this program.

Program 8 for a constant-current operated resistance thermometer: a TSI boundary layer hot wire sensor was operated cold as a resistance thermometer. Mean temperature, temperature fluctuations, and enthalpy thickness were collected using this program.

(C) Measurements of the Baseline Experiment on a Flat Surface

The baseline case was conducted over a flat surface with no streamwise pressure gradient. There were a total of fourteen streamwise locations for boundary layer measurements. At each location, 30 points across the boundary layer were sampled using a single hot wire probe first, followed by two cross-wire probes, one for measuring $\overline{u'v'}$ and another one for $\overline{u'w'}$. A 4-$\mu$m resistance wire, operated at constant current mode, was used to measure mean temperature distribution and temperature fluctuations.

This baseline case served as a qualifying test of the current experimental facility and apparatus. At the time when this report was written, only preliminary results of mean velocity profiles, streamwise normal stress, skin-friction coefficients, and Stanton number were available.

Velocity profiles at fourteen stations along the streamwise direction were measured. Five of these are shown in Fig.4. The transitional flow started at about $Re_x=5x10^5$. The mean velocity profiles showed close agreement with the Blasius profile in the laminar flow at $Re_x<5x10^5$, started to deviate from the Blasius profile in the transitional flow, and reached a fully turbulent flow at $Re_x>1.38x10^6$. The global transitional process can also be clearly observed from the variation of skin-friction coefficients in

Fig.5. $C_f/2$ coincides with the Blasius correlation at $Re_x<5x10^5$, starts to rise from the Blasius correlation at $Re_x=5x10^5$, and overshoots the turbulent correlation at $Re_x>1.38x10^6$. This overshoot in the beginning of the turbulent flow is common and has been verified in many previous studies. The mean flow structure of the baseline case was satisfactory; hence, the experimental facility and apparatus were considered adequate for performing natural transition boundary layer experiments.

While the flow was considered transitional at $Re_x=5x10^5$ and turbulent at $Re_x>1.38x10^6$, the heat transfer on the wall was observed to be slower to respond to the transitional process. In Fig.5, the Stanton number is in close agreement with the laminar correlation until $Re_x=7x10^5$ when it started the transitional process, and Stanton number was never able to reach the fully turbulent correlation at the end of the test section where flow was already turbulent. This slower response of heat transfer to the transitional process results to the breakdown of the Reynolds analogy in the transitional as well as in the low-Reynolds-number turbulent flows. This baseline study has successfully demonstrated the effect on the wall from the incoherence between the momentum and thermal transports in the transitional boundary layer. The continuing study will focus on finding how this occurs.

(D) Design and Fabrication of a Three-Wire Probe for Measuring Reynolds Heat Flux in a Transitional Boundary Layer

An intensive literature search has been made regarding the simultaneous measurement of crossstream velocity fluctuations and temperature measurement. Almost all the measurements, except one, were made in either a fully developed turbulent boundary layer or in a turbulent shear layer. For this study, special constraints of limited spatial and spectral resolutions have been imposed on the probe design for measuring Reynolds heat flux in the relatively thin and unsteady transitional boundary layer. One special feature of the three-wire probe is to raise the probe axis 10 degrees from the wall to reduce the probe/wall interference. This resulted in a non-conventional probe design with two velocity wires inclined at 35 and 55 degrees from the axis (Fig.6&7). This specially designed and custom-made three-wire probe was provided by TSI Corporation and was delivered in June. The specifications are:

(a) Velocity Sensor (X Array)

1. 2.5 μm platinum coated tungsten wire with copper plated ends.
2. 0.5 mm sensing length.
3. 1.0 mm total wire length (needle spacing).
4. 0.35 mm spacing (sensor to sensor).
5. Wires oriented 35 and 55 from main probe shaft as shown on Fig. 6&7.

(b) Temperature Sensor

1. 1.25 μm unplated platinum wire.
2. 0.35 sensing length (same as needle spacing).
3. Wire parallel to main probe shaft.
4. Spaced 0.35 mm from X array.

The two velocity wires will be operated at constant temperature mode with high overheat ratio, while the temperature sensor will be operated cold (very low overheat ratio) at constant current mode. The extremely small diameter of the temperature wire is necessary for obtaining adequate thermal frequency response about 1 kHz at low overheat ratio. Since one of the wires is very delicate, only about 1.25 um in diameter, an efficient and safe procedure has to be developed to calibrate the probe. The data reduction algorithm for Reynolds heat flux ($\overline{t'v'}$) has been developed and the computer program is being written. It is expected to have preliminary Reynolds heat flux measurements in November 1990.

## MAJOR ACTIVITIES IN THE SECOND YEAR OF THIS PROGRAM

The first year program has been proceeding smoothly following the proposed plan. The major activities planned for the second year are:

(a) Calibrate the three-wire, velocity-temperature probe and use it to measure Reynolds heat flux in the transitional boundary layer.

(b) Reduce the collected data of the baseline case and investigate the flow structures including energy budget, power spectra, and Reynolds normal and shear stresses.

(c) Use a conditional sampling technique to separate the non-turbulent part of the transitional flow from the turbulent part and study the effects of intermittency and turbulent spots on thermal transport.

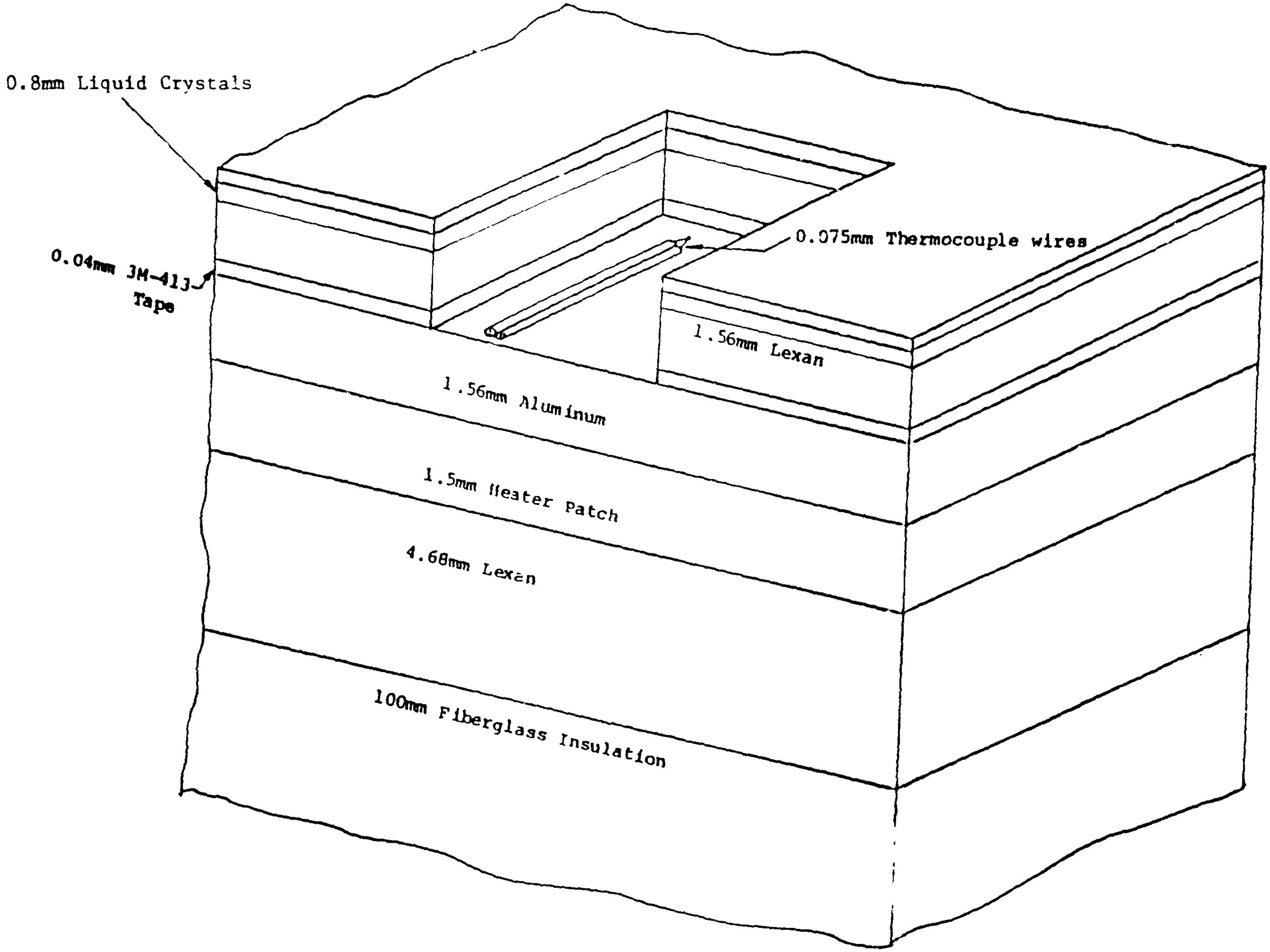


Figure 1. Cross-section of Heated Wall (not to scale).

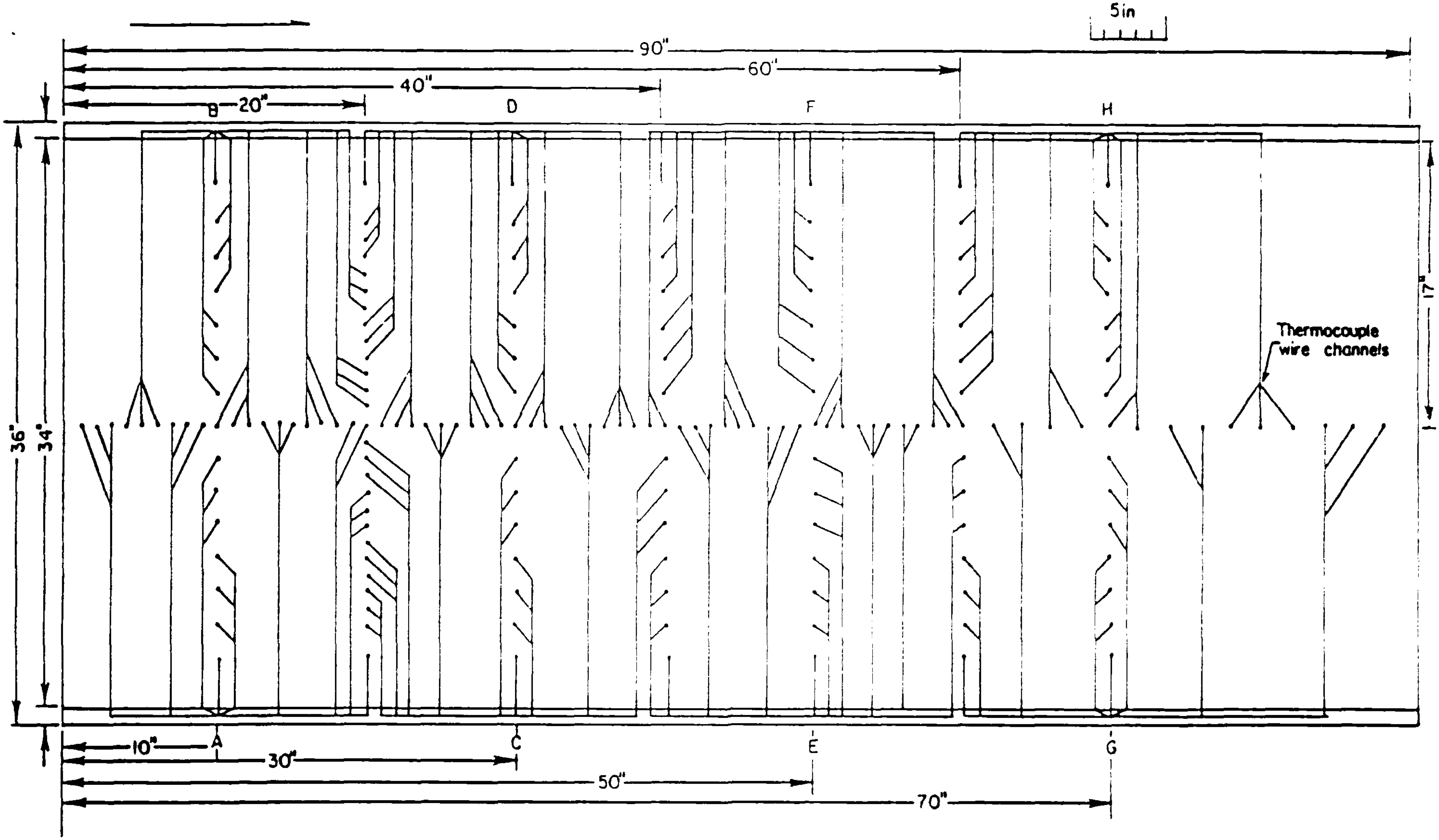


Fig. 1 Layout of thermocouples on the test wall.

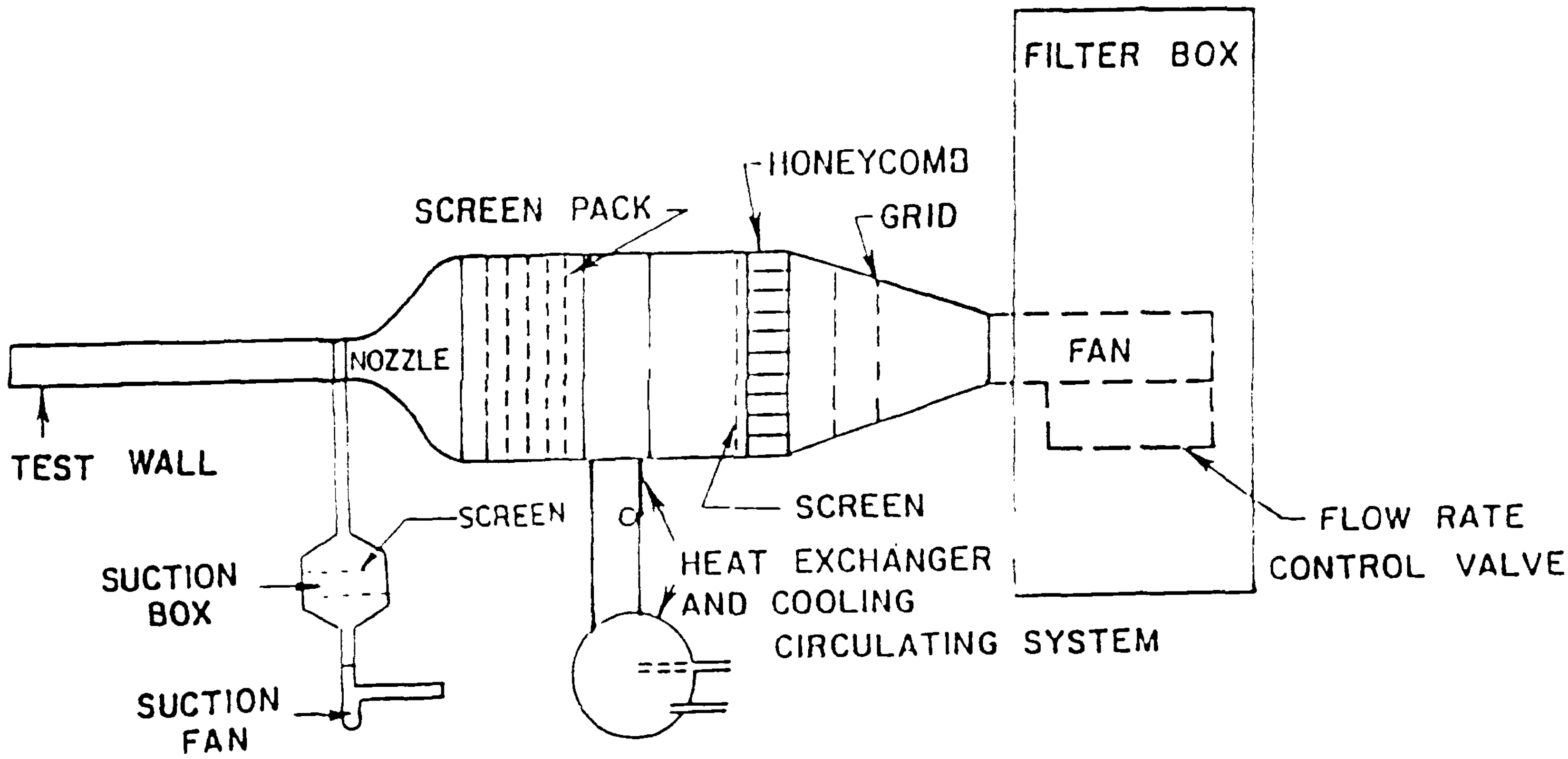


**Figure** 3. Plane View of the Wind Tunnel

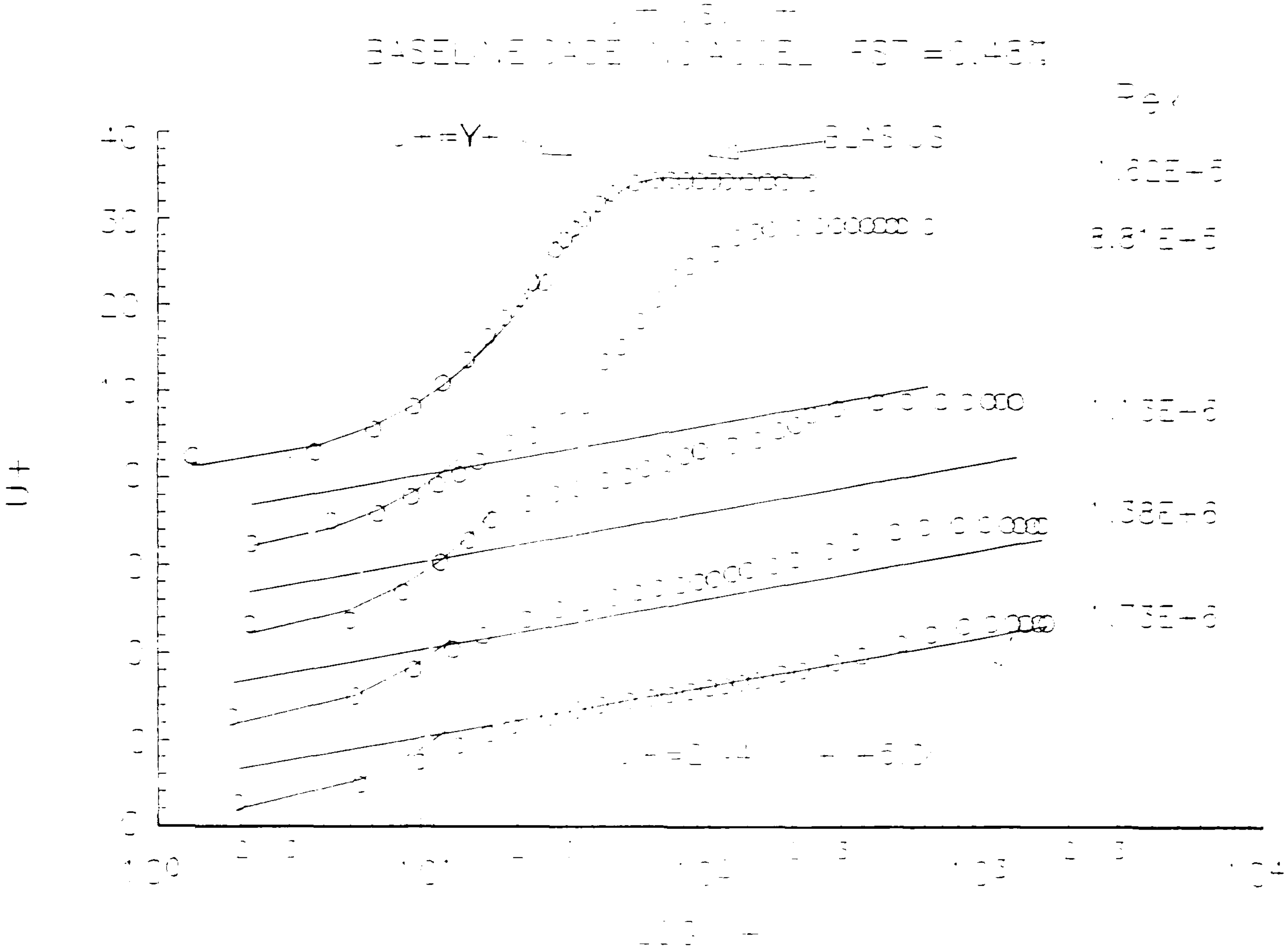


Figure 4. Mean velocity profiles.

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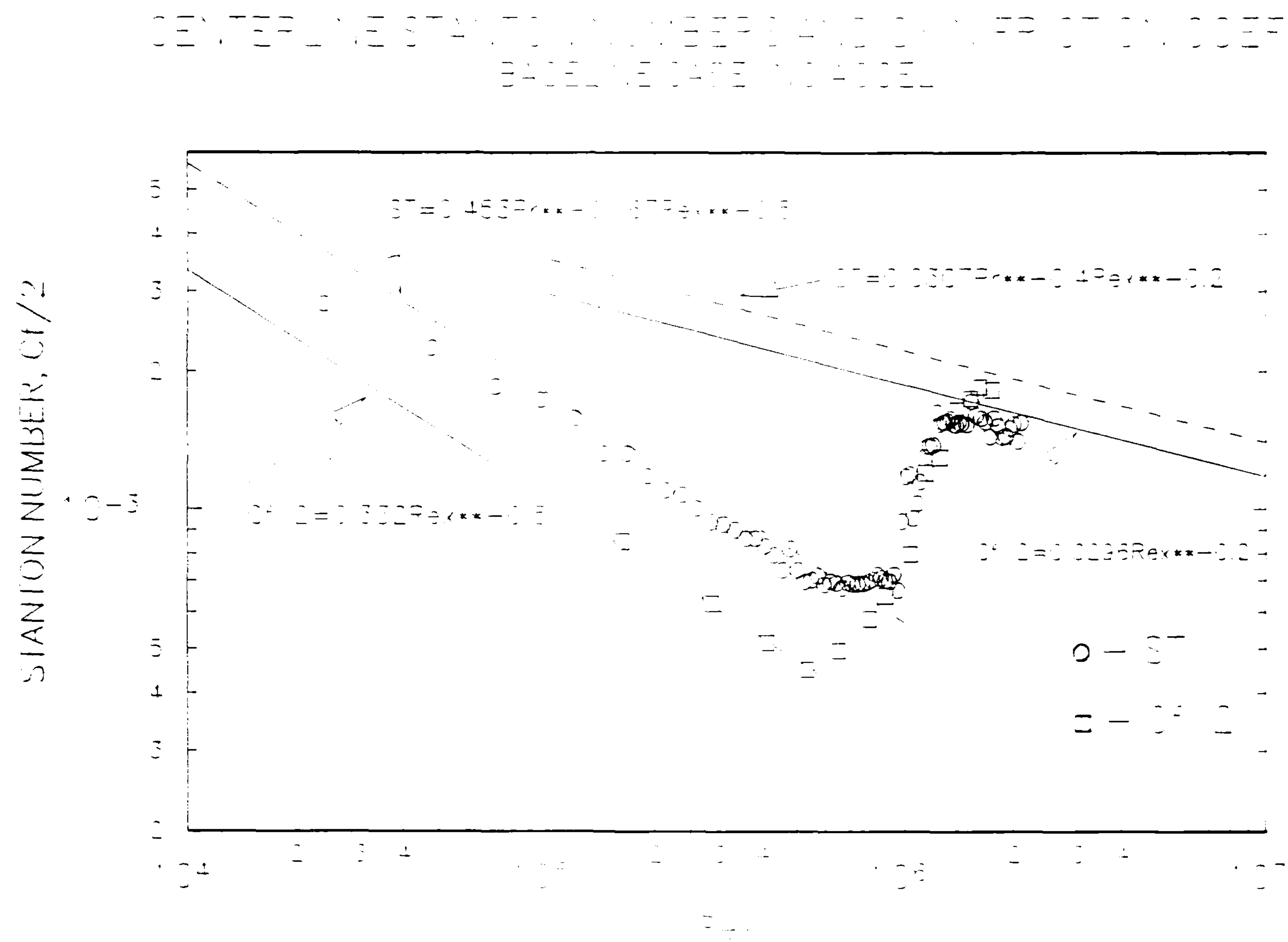


Figure 5.

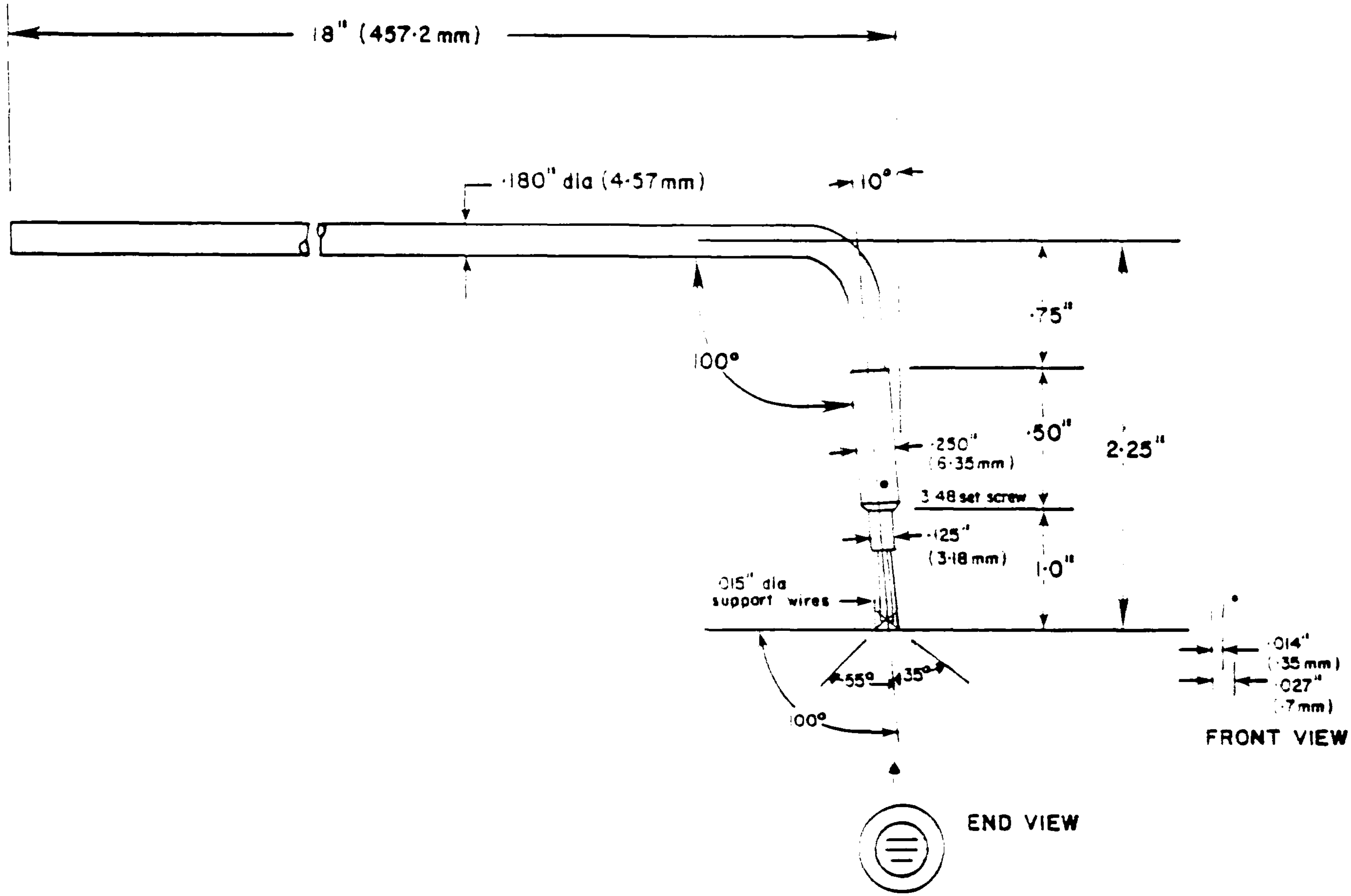


Figure [illegible]. 3-wire boundary layer sensor for measuring Reynolds heat flux

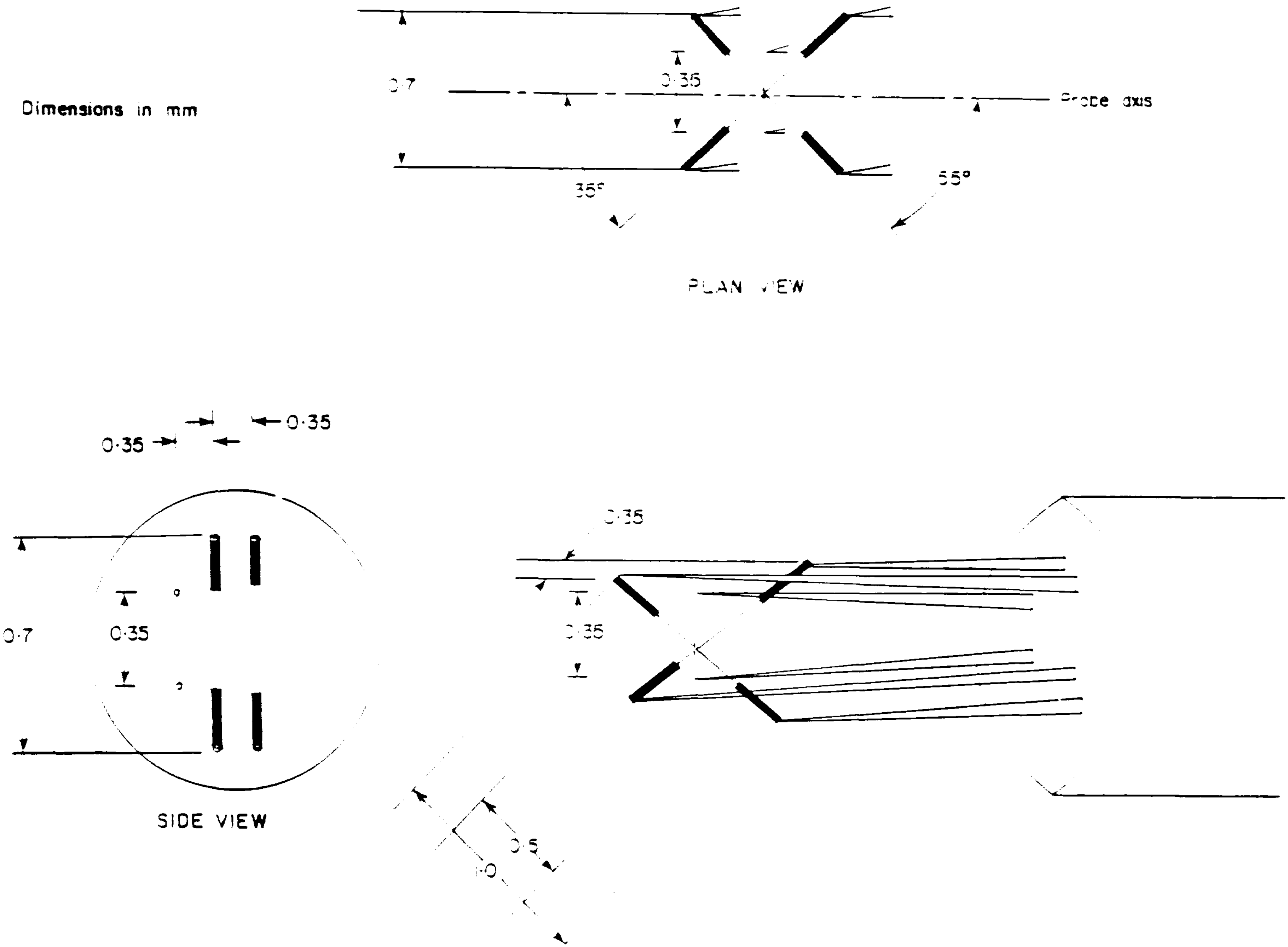


Figure 7. Close look of the wire arrangement of the 3-wire sensor.

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